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Abstract

The management of remanufacturing activities requires new techniques in order to improve these systems for cost optimized operations. However, several factors make the operations of the reverse logistics process difficult. In particular, uncertainties in quantity, quality and timing of returns negatively affect remanufacturing activities such as production planning and inventory control. In this paper, a remanufacturing process model is developed through a System Dynamics approach. The study focuses particularly on selecting and representing the relationships among sensitive factors such as residence time and return index which affect uncertainty on returns rate. The results of the simulation show how these factors can have more influence than an inventory/production strategy for companies involved in remanufacturing. Through the analysis of the total production costs, the results show a considerable increase in cost caused by changing the residence time. This finding suggests that knowledge of customer behaviour and product characteristics can be used to impact on reverse logistics.

Keywords: System Dynamics, Reverse Logistics, Remanufacturing, Management Strategy.

1 INTRODUCTION

Increasing pressure to improve market competitiveness has pushed companies to consider the reverse logistics process because of economic and environmental benefits. The modern trend, particularly for developed countries, is to use fewer environmental resources such as energy, water, air and material to manufacture products. Society and industry have recognized the limited availability of natural resources and are moving towards more environmentally-friendly products and recovery of resources. Moreover, the ever increasing number of manufactured products requires more and more natural resources. Trillions of tons of natural resources such as raw materials, energy and water are required for the manufacturing process and an average American uses 20 tons of materials every year (Gungor & Grupta 1999). Interest in strategic sustainability is growing among multinational companies as they develop sustainability reports to show both their interests in the environment and their responsibilities toward socio-ecological activities in conducting business. In addition, sustainability can be used as a competitive strategy to create company branding, comply with government regulations regarding the environment and optimize the cost of operational processes. Reverse logistics processes and particularly remanufacturing can have an important role in sustainability as well as in competitive strategies (Fuji Xerox 2007). The cost of remanufacturing is less expensive than the cost of manufacturing and increasing consumer interest in environmentally friendly products can enhance the image of the company and create competitive advantage

Several factors characterize a reverse logistics environment and these include: quantity, timing and quality of returns and complexity of the product, testing, evaluating and remanufacturing (Guide, Jayaraman & Linton 2003). These factors can differentiate the analysis and implementation of a returns system. For example, products, after the sale, may be used and returned within a different period of time and in different quantities. For this reason, the timing, quantity and quality of returns are uncertain and may depend on customer behaviours in using the products. This could affect the resource planning for methods and activities with which companies collect, test and remanufacture returned products. Moreover, product complexity due to a number of different constituent parts and components makes recovery and remanufacturing processes even more complex because of the number of activities that must be planned and controlled for each different part and component. However, the uncertainty in the quantity and timing of returns is one of the main factors which makes the implementation of reverse logistics processes difficult, particularly for the integration between the forward and reverse supply chains. For example, the difficulty in determining the quantity of used products returned by customers negatively affects remanufacturing and traditional production planning. Moreover, the lack of tools and guidelines in planning, controlling and managing remanufacturing operations limits the growth of the remanufacturing sector (Guide 2000). If not well designed, a returns system can increase company costs because of reverse logistics activities such as remanufacturing and disposal (Inderfurth 2005). For this reason, a company objective is to optimize an integrated reverse and forward supply chain system so as to minimize the total cost and consequently to obtain economic benefits.

In this paper, we use System Dynamics (SD) (Forrester 1958, 1961), a methodology for studying and managing complex feedback systems, more particularly business and social systems, to model a remanufacturing system in which production is integrated with remanufacturing processes in order to analyse the effects of external factors on returns rate. Returns rate is one of the main reverse logistics factors affected by uncertainty in timing and quantity of returns (Guide 2000). Our objective is to analyse, through the simulation of the SD model, the trend of the total production cost influenced by a returns rate which is affected by external factors such as *residence time* (time the products stay with the customers) and *return index* (an index which characterizes several products in different industries). In order to model this system, uncertainty in timing and quantity of returns is defined through the relationships of these factors which can provide a correlation between demand and returns. In our model, we considered a system with a pull inventory control strategy without disposal of recoverables and lead time in order to facilitate the modelling of the remanufacturing system.

2 LITERATURE REVIEW

The complexity of reverse logistics processes has motivated several researchers to use SD modelling techniques in the search for better strategies and policies for integrating the forward and reverse supply chains by addressing the effects of uncontrollable factors such as uncertainty of returns. However, there is still a lack of SD research for closed loop supply chains (Kumar and Yamaoka 2007). A System Dynamics simulation tool was developed to analyse the dynamic behaviour and the influence of the various activities on the reverse logistics network (Georgiadis & Vlachos 2004a). In particular, the objective of the research was to simulate a remanufacturing feedback loop to determine the effect of remanufacturing capacities and penalties on total costs under various scenarios. Penalties refer to an inappropriate collection and handling of used products imposed on companies by environmental legislation. It was found that total costs decreases when higher remanufacturing capacities are reached. In another similar study using System Dynamics (Georgiadis & Vlachos 2004b), the impact of environmental influences and remanufacturing capacity planning policies were simulated on the behaviour of a reverse logistics system. They analysed the effects of customer awareness of a company's green image on product demand and the environmental legislation on the collection rate of returns flow. The activities modelled in their systems included: supply, production, distribution, usage, returns collection, inspection, remanufacturing and waste disposal.

A remanufacturing system was modelled using SD to study the impact of product lifecycles on planning optimal collection and remanufacturing capacities for several kinds of products with different lifecycles and return characteristics (Georgiadis, Vlachos & Tagaras 2006). Two concepts were introduced in the study: *residence time* and *residence index*. *Residence time* is defined as the time the product stays with the customer before it is returned while *residence index* represents the ratio of the average residence time over the product lifecycle length. The residence index represents the tendency of the product to stay and be used by the customer during its lifecycle. It can be used to classify different products as to their suitability to be remanufactured or not. Their research focused mainly on the effect of product lifecycle on capacity planning. Thus, our motivation for this present research is that so far in the reverse logistics literature, no study could be found on the effects of returns rate and uncertainty in quantity of returns on total production.

3 MODEL FORMULATION

Our study is based on a single product remanufacturing system which involves several operations such as: production, collection and inspection of used products, remanufacturing and disposal. Our focus in this study is on returns of products from customers/products users at the end of their useful life; other returns such as product recalls and B2B commercial returns are excluded in the study.

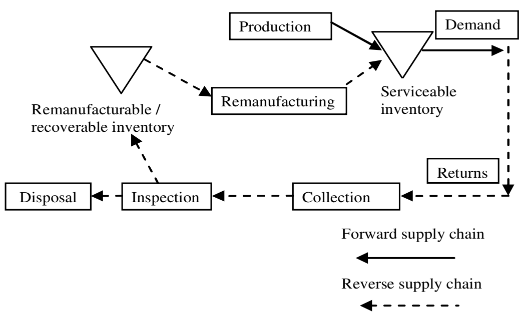

Figure 1. Remanufacturing Process

Figure 1shows the remanufacturing process considered in this paper. The forward supply chain involves production of new products to fulfil customer demand. After product use, returns are collected, inspected and either stored as remanufacturable/recoverable inventory or disposed depending on whether the quality of returns is suitable for remanufacturing according to the company's quality standard policy. The serviceable inventory, used to fulfil external demands, is fed by the production of new or remanufactured products which are as good as new. Important activities in the remanufacturing system are not only production and manufacturing but also include analysis and decisions to be made about inventory, operational and marketing activities.

A number of assumptions are considered in this analysis in order to simplify the system and its interpretation. Uncontrollable disposal is not considered. Thus instead of returning to the remanufacturer, it is disposed in uncontrollable ways, sometimes against producer suggestions or environmental regulations. The capacity of several activities such as collection, remanufacturing and production are considered infinite. However, the use of a pull system for inventory control involves production and remanufacturing up to levels which constrain production and remanufacturing batches. Moreover, backordering is not considered. The two major assumptions are: the definition of a returns rate which incorporates uncertainty in quantity of returns, and the use of a pull inventory control system. The returns rate, which is used to calculate the number of returns, is represented as a ratio between the probable returns flow of sold products and the forecasted demand. The probable returns flow is calculated through the relationship with the main factors which characterize the model of this study - product lifetime or service life and return index. These give a dependent relation between returns and demand.

A return index is considered as represented by the formulation:

(product lifetime / average residence time) / product lifetime = 1 / average residence time

where average residence time is the factor defined in the study of Georgiadis, Vlachos and Tagaras (2006). The factor in the numerator represents the number of times a kind of product could be returned during its lifetime. A return index, formulated in this way, could be considered as the frequency of the product returned by the customer during its lifetime. This frequency can vary among products which present different characteristics in several industries.

Our objective is to analyse, through a dynamic simulation, the total production cost of a remanufacturing system in which uncertainty on the quantity of returns characterizes the reverse flow. System Dynamics is a computer aided method for analysing and solving complex problems, particularly on policy analysis and design, with several applications such as corporate planning and policy design, economic behaviour, public management, biological and medical modeling, energy and environment, social science, dynamic decision making, complex non linear dynamics, software engineering and supply chain management (Angerhofer & Angelides 2000). A System Dynamics approach as a modeling and simulation method for dynamic industrial management processes could be an excellent tool for those management systems in which new decisions have to be made and new circumstances appear with the passing of time (Coyle 1996).

3.1 Causal loop diagram

A causal loop diagram (CLD) provides an understanding of the system structure as it identifies the important factors or variables influencing a system as well as the causal influence among these variables. A CLD consists of variables connected by arrows denoting the hypotheses and the mental models of the modeller in order to represent the feedback structure of systems which are responsible for a problem (Sterman 2000). Positive as well as negative feedback interrelationships can be represented through feedback or causal loops.

The CLD representing the remanufacturing model is presented in Figure 2. The behaviour of the system is defined by seven negative feedback loops labelled as N1, N2, N3, N4, N5, N6 and N7. These loops balance the system and push typical production and remanufacturing factors towards stable levels rather than causing them to grow exponentially. Negative feedback loops operate to control the output of activities in order to bring the state of the system towards a target value (Sterman 2000). Therefore, if the process presents outputs far from the target level, a negative feedback generates corrective actions to bring the process toward the desired value.

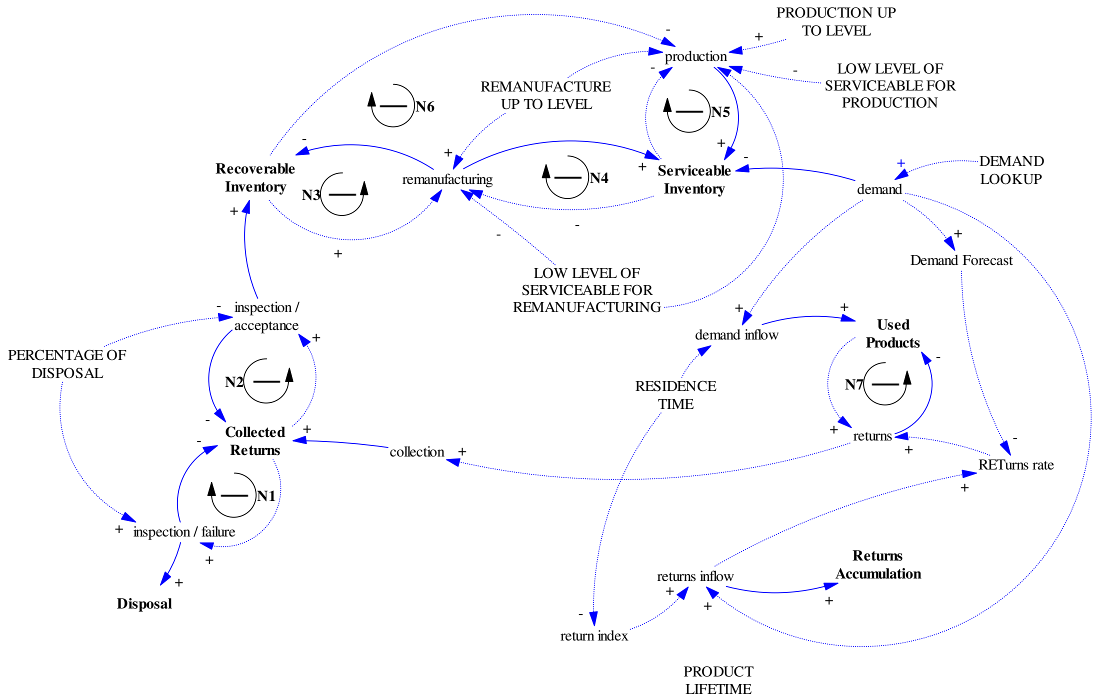

Figure 2. Causal loop diagram

The behaviour of the collection activity in this remanufacturing process is represented by two negative feedback loops, N1 and N2. An increase in *returns* increases the rate of *collection* which in turn increases the level of *Collected Returns*. At this stage, returned products are inspected in order to check for their quality and remanufacturability. Failed items decrease the level of *Collected Returns*, through an *inspection/failure* flow and at the same time increase the level of *Disposal* which represents the quantity of items not reusable and disposed of. The flow rate of failed items depends on the value of *PERCENTAGE OF DISPOSAL* which represents the quality standard policy of the company and is affected by several parameters and techniques used to check the returned items. It is defined as an average percentage of collected returns disposed of and differs for different products and different quality standard policies used. Thus, an increase in the value of *PERCENTAGE OF DISPOSAL* leads to an increase in the flow of failed items during the month. Since an increase in *Collected Returns* causes an increase in *inspection/failure* and which in turn causes a decrease in *Collected Returns*, a negative feedback loop (N1) is created. Accepted items increase the level of *Recoverable Inventory* ready to be remanufactured through the *inspection/acceptance* flow. The flow rate of accepted items depends inversely on the value of *PERCENTAGE OF DISPOSAL*, as a lower percentage of disposed items of leads to higher level of remanufacturable items. Thus, an increase in *inspection/acceptance* rate causes a decrease in *Collected Returns* level and which in turn causes a decrease in *inspection/acceptance* rate, hence forming the negative feedback loop N2.

The behaviour of the remanufacturing activity in the process is represented by two negative feedback loops, N3 and N4. Remanufacturable items are stored as *Recoverable Inventory* from which items are used for remanufacturing purposes when necessary and stored as *Serviceable Inventory* in order to fulfil customer *demand*. Remanufacturing occurs when necessary in a pull inventory strategy because remanufacturing is preferred to a more expensive production activity. Several models in literature discuss push and pull inventory strategies in a remanufacturing system (Kiesmuller 2003; van der Laan & Salomon 1997; van der Laan, Salomon & Dekker 1999).

In Figure 2, *Sr (REMANUFACTURE UP TO LEVEL)* and *sr (LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING)* are two variables which affect the *remanufacturing* rate and are used for implementing a pull strategy in the system. *Sr* represents the upper value limit for remanufactured batches while *sr* represents the lower value for re-manufactured batches as well as the level of a *Serviceable Inventory* for which a re-manufacturing batch is required. *Sr* - *sr* represents the level of

Recoverable Inventory for which it is possible to produce a remanufacturing batch. A more detailed explanation of the inventory pull strategy is given in Figure 3 which shows the usage of inventory over time in a remanufacturing system.

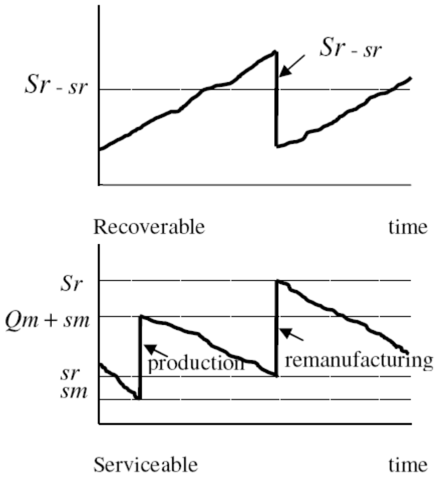

Figure 3.Usage of inventory in a remanufacturing system

Figure 3 is similar to van der Laan, Salomon and Dekker's (1999) who also did not consider disposal of recoverable inventory. The pull strategy is represented by the *Recoverable Inventory* level. When this level exceeds (*Sr* - *sr*) (i.e. the level at which it is possible to make a remanufacturing batch) disposal of items does not occurs. Remanufacturing occurs only when necessary and is represented by *sr*, the level of *Serviceable inventory*. This strategy increases the cost of the *Recoverable Inventory* but reduces the cost of the *Serviceable Inventory* which is usually more expensive. Remanufacturing is preferred to production as *sm*, the *Serviceable Inventory* level at which a production batch is required is lower than *sr*.

An increase in the *Recoverable Inventory* level increases the *remanufacturing* rate which in turn decreases the *Recoverable Inventory* level forming the negative feedback loop N3 as shown in Figure 2. Similarly in the negative feedback loop N4, an increase of *remanufacturing* level increases the *Serviceable Inventory* level which in turn decreases the level of *remanufacturing* activity. Thus, inventory levels have both positive and negative effects on the *remanufacturing* rate in order to control the flow of remanufacturing items and achieve balance in the inventory system.

In the system, *production* is only used to increase the *Serviceable Inventory* level when *remanufacturing* is below *Recoverable Inventory* as shown in Figure 3. Two additional variables which affect production flow are used to implement the pull inventory strategy: *Qm* (*PRODUCTION UP TO LEVEL)* is the upper value for production batches and *sm* (*LOW LEVEL OF SERVICEABLE FOR PRODUCTION)* is the level of serviceable inventory at which a production batch is required. However, production flow is mainly affected by *Sr* and *sr*, because it is only when the *Recoverable Inventory* level is lower than *Sr* - *sr* and the *Serviceable Inventory* level reaches *sm* that a production batch is manufactured and stored in *Serviceable Inventory*. The negative feedback loop N5 creates a balance between *production* flow and *Serviceable Inventory* level.

The negative loop N6 involves both the *production* and *remanufacturing* flows and both the *Recoverable* and *Serviceable Inventory* level as shown in Figure 2. In this remanufacturing system a balance among these variables, which involves a control process between inventory levels and flow of items, is required. For example, if the physical flow of items produced increases, the *Serviceable Inventory* level increases. In order to prevent a continuous accumulation of serviceable items (without considering depletion from customer demand), *Serviceable Inventory* affects negatively the *remanufacturing* flow which consequently decreases. This leads to an increase of *Recoverable Inventory* level and consequently, due to the negative relationship between *production* and *Recoverable Inventory*, *production* flow decreases. In this way the system is driven towards a balancing goal.

The behaviour of negative feedback loop N7 is caused mainly by *Used Products* and *returns* as well as several variables representing the influence relationships between the forward and reverse logistics. The process starts with customer *demand* which depletes the *Serviceable Inventory* level. Product demand or sales are defined by external historical data represented by *DEMAND LOOKUP*. After a period of time or *RESIDENCE TIME*, products in use can be considered as used products. This is represented by the flow between the rate variable *demand* inflow and the level *Used Products*. The variable *RESIDENCE TIME* is the average time that a product stays with its customer before it is returned (Georgiadis, Vlachos & Tagaras 2006). This period of time varies for different kinds of products and different customer behaviours. For this reason, in this model, not all used products are considered as returns but as possible returns. This represents the uncertainty which affect the returns quantity in a closed loop supply chain. Part of the used products becomes *returns* which are consequently collected. This is represented by the physical flow for which *returns* deplete the *Used Products* level and the information flow between *returns* and *collection*. Also in this case, the level of used products positively affects and controls the flow of returns, generating the negative loop N7, which characterizes the possibility that not all used products are returned at the same time.

Uncertainty in the quantity of used products returned by customers negatively affects collection, remanufacturing and production planning. For this reason, several variables, shown in Figure 2, are used to reduce the effect of uncertainty and set the quantity of returns. The *return index*, related to the *RESIDENCE TIME*, is used to set the number of possible returns from the customer demand. This is represented by the *returns inflow* which is influenced by the *returns index* and *demand*. In order to set the number of returns from used products a *returns rate* is used which is generated through the relationship with possible future *Demand Forecasts* and possible returns from *demand*. Finally, *PRODUCT LIFETIME* is not related to any of the variables in the system but it is shown in Figure 2 as it gives a better interpretation of the variable *return index*.

3.2 Stock and flow diagram

In order to give a quantitative point of view to the model, a stock and flow diagram (SFD) is used to study the characteristics of the process. Through the SFD, it is possible to analyse the dynamic characteristics between rate and level variables and define the relationships among the variables of the model. These relationships are used to establish mathematical equations in order to run simulations of the model. Coyle (1996) states that while the causal loop diagram represents a real system through variables connected by signed links, a quantitative model represents the same system using variables in equations. Figure 4 shows the stock and flow diagram of the causal loop diagram shown in Figure 2.

Rectangles represent level or stock variables which are accumulations of items while valves represent rate or flow variables which are physical flows of items feeding or depleting the stocks. Physical flows of items are represented by double line with arrows while flows of information (connection among variables and their relationships for mathematical formulations) are represented by single line with arrows. Auxiliary variables shown in all upper case letters represent constants and while those in lower case letters represent converters used in calculations.

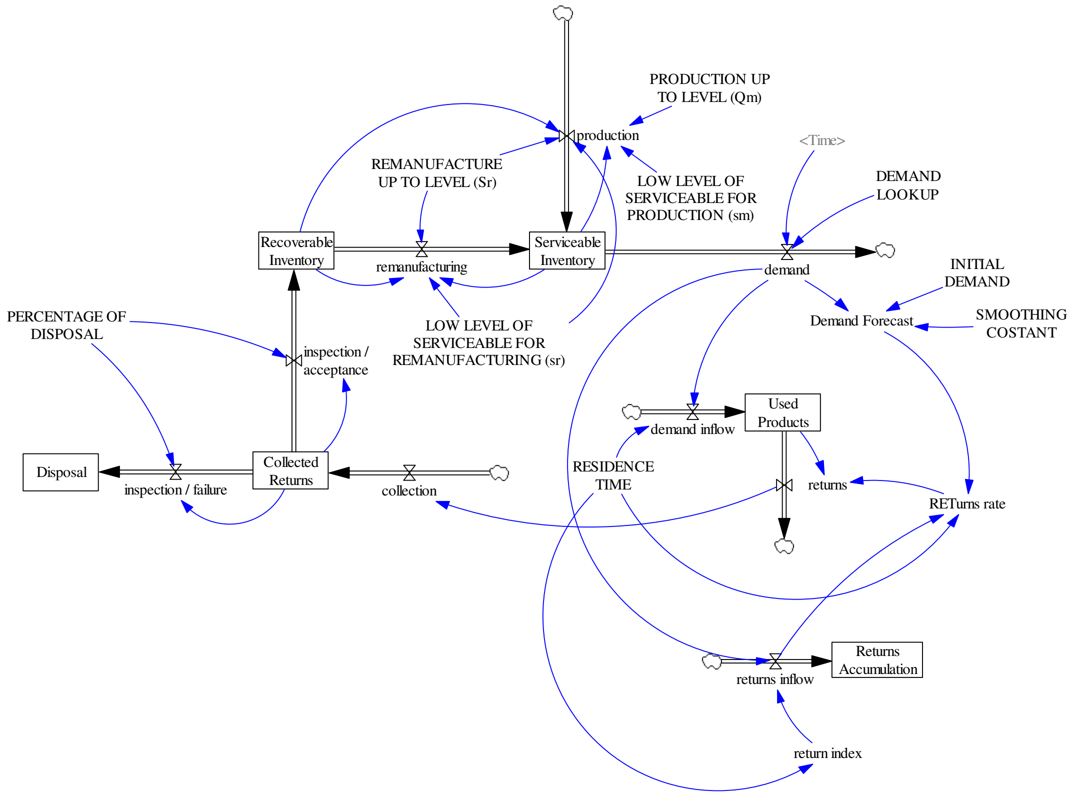

Figure 4. Stock and flow diagram

3.3 Mathematical formulation

The dynamic behaviour of the remanufacturing system is implemented by a set of mathematical equations which is described next. The dynamic behaviour of the level variables such as *Collected Returns*, *Recoverable* and *Serviceable Inventory* and *Used Products* is given by a time integral of the net inflows minus the net outflows. The equation below computes the value of the level of *Collected Returns* at time *t*, through the difference between the *collection* inflow and the two outflows, *inspection/acceptance* and *inspection/ failure*:

$$Collected\ \ Returns(t) = \int_0^t (collection(t)\ -\ inspection/acceptance(t)\ -\ inspection/failure(t))dt\ +$$

$$Collected\ Returns\ (t\text{-}dt)$$

The *collection* flow is equal to the *returns* flow. This means that at time *t*, all returns follow a collection process; *collection (t) = returns (t)*. Infinite collection capacity is assumed as all the possible returns are collected. Failed returns at time *t* are equal to total *Collected Returns* times the *PERCENTAGE OF DISPOSAL*. The percentage of disposed returns is considered constant as this is due to the difficulty in representing and modeling the real dynamic variance for this factor which depends on product characteristics, company quality policy and inspection strategy. This particular problem is not within the scope of this study. Accepted returns at time *t* are the *Collected Returns* that passed the inspection process. For this reason, the percentage of returns accepted for remanufacturing is 1 – disposal percentage:

*inspection/acceptance (t) = Collected Returns (t) * (1 – PERCENTAGE OF DISPOSAL)*

*inspection/failure (t) = Collected Returns (t) * PERCENTAGE OF DISPOSAL*

An *IF THEN ELSE* function and the logical operator *AND* are used to define the production quantity in the process. In particular, they provide the number of production batches during the simulation period. The logical expression defines the condition when the *Serviceable Inventory* level is less than or equal to the *LOW LEVEL OF SERVICEABLE FOR PRODUCTION* and also when *Recoverable Inventory* level is less than *REMANUFACTURE UP TO LEVEL* minus *LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING*. If the condition is true, the expression returns a production batch equal to *PRODUCTION UP TO LEVEL* minus *LOW LEVEL OF SERVICEABLE FOR PRODUCTION*, otherwise the returned value is zero. A similar equation defines the remanufacturing quantity and the number of remanufacturing batches in the model. In this case, the condition requires that *Serviceable Inventory* level is less than or equal to *LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING* and that *Recoverable Inventory* is greater than or equal to *REMANUFACTURE UP TO LEVEL* minus *LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING*. The possible returned values are a remanufacturing batch equal to *REMANUFACTURE UP TO LEVEL* minus *LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING*, if the condition is true, or zero otherwise.

A functional relationship between two variables is used for the formulation of the *demand* or sales of product at time *t*. This is obtained using a lookup function which allows the definition of a customized relationship between a variable and its causes defined as a table of values. Table *DEMAND LOOKUP* is defined using historical data for product demand or sales obtained directly from the Global Market Information Database (GMID). The database provides historical data, forecasts and statistics analysis for many countries worldwide on consumer goods for several industries, companies and brands. An equation gives the value of *demand* for at any time through a linear interpolation between the values specified in *DEMAND LOOKUP* as *demand (t) =DEMAND LOOKUP (Time).*

Demand inflow represents the flow of previously sold products currently in use which now are used products and possible returns after the *residence time* has elapsed. In order to model this process the function *DELAY FIXED* is used. This function returns the value of the input *demand* delayed by the delay time which in this case is the *residence time*.

The variable *return index* is formulated as the reciprocal of the *RESIDENCE TIME* as follows:

$$return\ idex\,(t) = \frac{(PRODUCT\ \ LIFETIME\ /\ RESIDENCE\ TIME)}{PRODUCT\ \ LIFETIME} = \frac{1}{RESIDENCE\ TIME}$$

This *return index* represents the frequency of a particular product to be returned by customers. A number of products (and their components) such as cameras, mobile phones, computers, printers and tyres can be remanufactured several times during their lifetime. For this reason, the same product (or component assembled into the product) can be placed on the market with an as good as new condition and subsequently returned several times. The numerator in the equation defines the number of times a particular product can be returned during its lifetime while taking into account its *residence time*. For example, a product with a lifetime of approximately twelve months and a *residence time* of two months could be returned six times. This is obviously an approximation of realistic circumstances where product characteristics and customer behaviour affect the return process. The denominator in the equation represents the total number of times the product can be returned. The product with a lifetime of twelve months can be returned twelve times during this time period.

The flow of actual returned items which are collected is represented as the minimum value between the portion of *Used Products* through the use of *a returns rate* and the total quantity of *Used Products*. This is expressed by the equation:

$$returns(t) = MIN\ (\ Used\ Products\,(t) *\ \ returns\ rate\,(t), Used\ Products\,(t)\ )$$

Products currently in use increase and feed the *Used Products* levels or possible returns, after their residence time. From this accumulation of possible returns, some items are effectively returned with a consequent reduction of *Used Products*. *Returns rate* represents the portion or percentage of used products which are returned during the time period under consideration. Several authors such as Kiesmuller (2003), Kiesmuller and Minner (2003) and Inderfurth (2005) use returns rate in their models. In order to define the quantity of returns, they consider the returns rate as a ratio between the average returns and the average demands. Consequently, the returns rate in this model is represented as a dynamic ratio between *returns inflow* and *demand forecast*. This is expressed by the equation:

returns rate(t) = returns inflow (t)/Demand Forecast (t). Returns inflow represents the expected returns of demand or sold products. A forecast of returns is obtained using the *return index*: $returns\ inflow(t) = demand\ (t) *\ \ return\ index\ (t)$

4 MODEL TESTING AND NUMERICAL INVESTIGATION

The structure of the model was validated using extreme condition tests (Sterman 2000). Under extreme condition of the inputs values such as zero or infinity, the model should behave as a realistic system. Validation was performed by means of direct tests for to the model equations and in particular to the flow equations. Extreme values were assigned simultaneously to all the input variables in order to analyse the value of the output which should be reasonable for a real system under the same extreme condition (Barlas 1996). The Reality Check function of the Vensim simulation was used to achieve this.

After validation, the model was simulated through a numerical investigation of the developed mathematical equations and the system objectives. The simulation horizon was set to 50 months with a time step of one month. Parameter values were: 0.1 for the *PERCENTAGE OF DISPOSAL*, 1000 units for *LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING*, 5000 units for *PRODUCTION UP TO LEVEL*, 500 units for *LOW LEVEL OF SERVICEABLE FOR PRODUCTION* and 0.1 for the value of smoothing constant for the *DEMAND FORECAST*.

Historical data of sales for mobile phones in Australia were used as input for the model simulation in order to simulate demand. A mobile phone is a product that presents an average residence time of around 18 months and a lifetime of 3-4 years (Georgiadis, Vlachos & Tagaras 2006). The total sales of the product and the percentage of market share for a particular company for the last six years were taken from the GMID database. The objective of the simulation was to determine the effects of *return index* on the total production costs for a remanufacturing system where the pull strategy is used. Hence, the numerical investigation was set up to perform six possible combinations of three *RESIDENCE TIMES* (6 months, 12 months and 24 months) and two remanufacturing batches (*REMANUFACTURING UP TO LEVEL*) (5000 and 6000 units). Total production cost is given by the sum of several operational costs such as disposal cost, holding cost for recoverable and serviceable inventory, remanufacturing and production costs. Holding cost for serviceable inventory and production activities are considered greater than holding cost for recoverable inventory and remanufacturing activities cost respectively. Unit costs are set to: $50 for disposal cost, $0.2 for recoverable holding cost, $0.4 for serviceable holding cost, $30 for remanufacturing cost and $100 for production cost.

5 SIMULATION RESULTS AND DISCUSSION

Simulation of the same size of remanufacturing batch with a *residence time* of 6 months resulted into a higher average total production cost, compared to 12 and 24 months of *residence time*. This is due to a greater value of *returns rate* and consequently a larger use of remanufacturing and disposal activities. However, when the *residence time* is increased from 12 to 24 months, the average total cost starts to increase. This could be due to an increase in production activities which are more expensive than remanufacturing activities. For the same residence time, a lower remanufacturing batch is less expensive. However, this difference in cost is less than the increase caused by changing the residence time. Thus, the results of the simulation lead to several observations. First of all, total production costs, *residence time* and consequently the *return index* were found to have more influence on inventory and production activities than company strategies. For these reasons, companies involved in remanufacturing systems should aim for a value of the *residence time* which causes the lowest total production cost.

Residence time is influenced by either customer behaviour in using the product or product characteristics. Although companies cannot influence customer behaviour in order to control residence time, they can do so through product characteristics. For example, changes in product design so that the product can be easily disassembled can help in reducing the variability of the *residence time*. A good example is the new tendency for the photocopier industry to develop products built using a modular format where all modules or components can be remanufactured (Fuji Xerox 2007). This process can generate a greater stability of the residence time of the components, which are easier to recover, than the whole product.

Nevertheless, the uncertainty generated by customer behaviour in using products has a significant influence on the returns process and total cost of production. In the simulation, an increase of the *residence time,* which involves a decrease of the *return index*, leads to lower possible returns and eventually a lower *returns rate*. In a previous study, this has already been observed, as products with shorter *residence time* have higher *returns rate* and possibility of profitable remanufacturability (Georgiadis, Vlachos & Tagaras 2006). However, in our analysis different customer behaviour in using the product can affect uncertainty on *returns rate*. For this reason, companies with knowledge of the behaviour of their customers can forecast more accurately the number of returns. The possibility of using incentives such as lease contracts, product service agreements with the customer and marketing/promotion programs for returned products can generate a higher level of control on customer behaviour and consequently on the *residence time* and *return rate*. For these reasons, a better forecast of the number of returns through knowledge of customer behaviour and changes in product characteristics can influence production, remanufacturing and inventory activities and consequently total production costs.

6 CONCLUSION

A System Dynamics approach was used to model and simulate a remanufacturing process where the *returns rate* is formulated through reverse logistics factors such as the *residence time* that products stay with customers and a *return index* which characterizes the return frequency of used products. These factors can control and at the same time reduce the uncertainty on *returns rate* by using a correlation between *demand* and *returns*. The remanufacturing system was implemented using a pull inventory strategy.

Using an analysis of total production costs, several observations were made with regard to the effects of the *residence time* and changes of the remanufacturing batch on such a process. The main observation is that customer behaviour and product characteristics have significant influences on the uncertainty of *returns rate* and ultimately on total production costs. Changes in product characteristics and the use of incentives for recovering used products can influence customer behaviour in the returns process and consequently improve control on *returns rate*. The latter, as the analysis of the simulation shows, can have a higher impact on total production cost optimization than production/inventory control strategies through changes in the volume of remanufacturing quantities. However, further investigations, particularly on the assumptions considered in order to simplify the analysis of the system, could be a topic for further research in the remanufacturing sector.

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